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A SEARCH FOR RADIATIVE NEUTRINO DECAY FROM SUPERNOVAE

Data Analysis Procedures

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1. INTRODUCTION

This document presents the data analysis procedures proposed for use with COMPTEL instrument aboard the Compton Gamma Ray Observatory in the search for radiative neutrino decay from supernovae. The proposed analysis methodology is an extension of a standard procedure used by the COMPTEL team in searching for a variety of source types. We have applied the procedures to a set of simulated data to demonstrate the feasibility of the method to this project.

2. ν DECAY SIMULATION

A computer model has been developed which simulates the radiative decay of a massive neutrino species. Specifically, the simulation generates neutrino spectra relevant for type-II supernovae and allows the neutrinos to stream from the surface of a proto-neutron star and decay in flight. An expanding spherically-symmetric shell is assumed and the appropriate relativistic kinematics are used. We have shown [1, 2] that the gamma ray spectra and intensities are dependent upon when in its history the supernova is observed, the supernova distance, the length of the observation period, and the postulated neutrino mass, lifetime and radiative decay branching ratio ($m_\nu, \tau_\nu, B_\gamma$).

Thus for a given COMPTEL supernova observation the first step in the data analysis chain is to generate gamma ray energy/angular distributions for a range of neutrino mass, lifetime and radiative decay branching ratios which correspond to a 3-D grid in the $(m_\nu, \tau_\nu, B_\gamma)$ -parameter space. These energy spectra and angular distributions can then be compared with the relevant COMPTEL data to search for the existence of radiative neutrino decay, and hence the existence of a massive neutrino species.

3. MAPPING ν SIMULATION TO COMPTEL DATASPACE

Our simulation of radiative neutrino decay from supernovae produces a gamma ray energy spectrum and an angular distribution for given values of m_ν , τ_ν and B_γ . However, the comparison of the expected energy spectra from radiative neutrino decay with the COMPTEL data is non-trivial. As is well known the COMPTEL instrument does not measure the energy spectrum of a source directly. The relevant parameter for a Compton telescope is the scattering angle ϕ which is defined through

$$\cos\phi = 1 - mc^2 \left(\frac{1}{E_2} - \frac{1}{E_1 + E_2} \right) \quad (1)$$

where E_1 and E_2 is the energy deposition in the D1 and D2 modules, respectively. Therefore, to search for the decay gamma ray emission from radiative decay we must map the

energy and angular distributions into the COMPTEL dataspace.

We take the approach described by de Boer, et al[3]. The COMPTEL data space consists of three parameters: χ, ψ, ϕ . The first two parameters represent an arbitrary spatial coordinate system centered on the COMPTEL pointing axis and the third the scattering angle defined above. The COMPTEL dataspace response to a source (in the locally flat approximation) is a cone with apex at (χ_o, ψ_o) , the source position, running at an angle of 45° with the (χ, ψ) -plane. However, because of finite resolution of event location within the detector modules, and energy measurement and deposition (which determine the scattering angle ϕ) the cone becomes a mantle. The density of events along this mantle is given, for a particular gamma ray energy E_γ , by the Klein-Nishina cross section. This mantle defines the PSF, $f(\chi, \psi, \phi; \chi_o, \psi_o, E_\gamma)$.

The expected number of events due to a *point* source located at (χ_o, ψ_o) with intensity distribution (or energy spectrum) $I(\chi_o, \psi_o; E_\gamma)$ is given by

$$e(\chi, \psi, \phi; E_\gamma) = g(\chi, \psi) \int I(\chi_o, \psi_o; E_\gamma) A(\chi_o, \psi_o; E_\gamma) T f(\chi, \psi, \phi; \chi_o, \psi_o, E_\gamma) dE_\gamma \quad (2)$$

while for a source with an angular distribution *different* from a point source

$$e(\chi, \psi, \phi; E_\gamma) = g(\chi, \psi) \int I(\chi', \psi'; E_\gamma) A(\chi', \psi'; E_\gamma) T f(\chi, \psi, \phi; \chi', \psi', E_\gamma) d\chi' d\psi' dE_\gamma \quad (3)$$

where, $g(\chi, \psi)$ is a geometrical absorption factor due to the finite size of the instrument (assumed to be independent of ϕ), $A(\chi', \psi'; E_\gamma)$ is the effective area for a given photon arrival direction (χ', ψ') , and T is the integration time. The discretized form of this is

$$e(d) = g(d) \sum_{E_\gamma} \sum_s f(d, s; E_\gamma) I(s; E_\gamma) X(s; E_\gamma) \quad (4)$$

where, $d = (\chi, \psi, \phi)$ a dataspace bin, $s = (\chi', \psi')$ a sky pixel bin, and $X = AT$ the exposure. Thus the second step in the data analysis chain is to map the output of the ν decay simulation into the COMPTEL dataspace using the procedure outlined above. Once the expected number of events for each dataspace bin is computed the search for radiative neutrino decay can proceed as discussed below.

4. SEARCHING FOR A SOURCE

To compare our ν decay simulation (after mapping into the COMPTEL dataspace) with the actual observational data we will use the Likelihood Ratio Method (LRM). Using our decay simulation and the mapping procedure described above we can determine *a priori* the number of gamma rays expected for each dataspace bin given a particular COMPTEL observation period, an assumed value of m_ν, τ_ν , and B_γ (or range of values), and a source distance (redshift). In general the expected number of events per dataspace bin is given by (see section 3):

$$e(d) = \begin{cases} B(d) & \text{if } H_o \\ B(d) + g(d) \sum_{E_\gamma} \sum_s f(d, s; E_\gamma) I(s; E_\gamma) X(s; E_\gamma) & \text{if } H_\nu \end{cases}$$

where $B(d)$ is the dataspace event density due to galactic diffuse, instrumental, and known source emissions, and H_o and H_ν represent the hypotheses for background alone and background plus neutrino decay, respectively. With these assumptions we can assign a likelihood to a dataspace of n bins under a given hypothesis H as

$$L(\{n_i\}; H) = \prod_{i=1}^n e_i^{n_i} \exp(-e_i)/n_i! \quad (5)$$

where n_i is the observed number of counts in bin i . The likelihood ratio is defined by

$$R = L(\{n_i\}; H_\nu)/L(\{n_i\}; H_o) \quad (6)$$

and it has been established that $\lambda = 2 \log R$ will adopt a χ^2 distribution with 3 degrees of freedom (ie., $m_\nu, \tau_\nu, B_\gamma$) in the event that the hypothesis H_o is true. Thus the third step in the data analysis chain is to form the parameter λ for each sampled grid point in the $(m_\nu, \tau_\nu, B_\gamma)$ -parameter space.

5. ANALYSIS PROCEDURE

For a given supernova, gamma ray energy spectra/angular distributions are generated for values of $m_\nu, \tau_\nu, B_\gamma$ based on the source's distance (redshift) and a specific COMPTEL observation period. Using the methodology outlined above we can test for the presence of radiative neutrino decay from a specific supernova as follows:

1. Determine the expected number of events per dataspace bin for hypothesis H_o (which includes background and any **known** sources).
2. Compute the likelihood function $L(\{n_i\}; H_o)$.
3. Given a value of m_ν, τ_ν and B_γ , compute the expected number of events per dataspace bin. This represents hypothesis H_ν .
4. Compute the likelihood function $L(\{n_i\}; H_\nu)$.
5. Calculate λ .
6. Repeat steps 3 → 5 for all values on the 3-D grid in $(m_\nu, \tau_\nu, B_\gamma)$ -parameter space.
7. Find grid point with maximum λ . This is the best fit point.
8. If $\lambda_{max} \geq \lambda_c$ (TBD) we reject the null hypothesis (H_o), and can exclude grid points in $(m_\nu, \tau_\nu, B_\gamma)$ -parameter space if they satisfy the condition $\lambda \leq \lambda_{max} - \chi^2_3$.
9. We claim a positive detection of radiative neutrino decay if $\lambda_{max} \geq 5\sigma$.

By keeping a record of the mass and lifetime parameters sampled and the corresponding λ values we can generate an exclusion plot in $(m_\nu, \tau_\nu, B_\gamma)$ -parameter space for each supernova observation, and as a final data product produce a exclusion plot for all supernovae observations combined. This method has the advantage that exposure and sensitivity differences between different observation periods, sources, and spacecraft status' are included in the calculations and thus combining the results from multiple observations

Table 1: Sources/Observation Periods

SN	Obs. Period	Source		GRO z-axis		Off-Axis Angle (deg.)
		RA	DEC	RA	DEC	
1987A	6	083.86	-69.27	091.28	-67.27	3.0
1987A	17	083.86	-69.27	083.48	-72.27	3.0
1993J	216	147.86	69.30	143.66	71.46	4.7

should be straight forward.

6. SUGGESTED SOURCES

The astrophysical sources which will be used to carry out this search are supernovae of type-II. We restrict our search to type-II supernovae since it has been shown experimentally [4, 5] that neutrinos are emitted during the collapse and cooling of the progenitor. In addition, the measured flux and energy of the electron-antineutrino burst from SN1987A was essentially the same as the predictions made with computer simulations of core-collapse supernovae. Thus we assume that, at least in neutrinos, type-II supernovae are standard candles.

To sample the largest region of $(m_\nu, \tau_\nu, B_\gamma)$ -parameter space the search should be performed with a combination of nearby and extra-galactic supernovae. Observations of SN1987A will allow a very sensitive search for massive neutrinos \geq few·100 eV because of its relatively close proximity, while extra-galactic supernovae which occur within COMPTEL's field of view will allow a search for a less massive neutrino. Observations of the recent type-II supernova SN1993J in M81, at approximately 3.2 Mpc, will allow a region of parameter space to be sampled which would not be sensitively sampled by any other known source. We therefore recommend that the search for radiative neutrino decay concentrate on the sources and COMPTEL observation periods given in Table 1. It is also possible that a region of the parameter space not sampled by SN1987a or SN1993j will be accessible if an extragalactic supernova occurs serendipitously within the COMPTEL field of view (near the pointing axis).

7. APPLICATION

As an example of the analysis procedures described above, we have processed two of the suggested sources to determine the general results which can be obtained. It should be stressed that the goal here is not to duplicate or estimate the results of a more detailed analysis to be completed in the near future, but rather to study the feasibility and overall features of the analysis technique.

For this analysis a number of assumptions have been made: a) the effective area of COMPTEL is fixed at 30 cm^2 , b) energy and angular resolution is perfect, c) the geometrical absorption factor is fixed at 1, and d) the diffuse gamma-ray background is assumed uniform and no other sources are present in the COMPTEL FOV. During this visit we hope to reconcile these assumptions and, with the help and experience of the COMPTEL team, incorporate accurate models of the energy, off-axis angle, and position

Table 2: Input Parameters - ν Decay

SN	Obs. Period	Distance (Mpc)
1987A	6	0.055
1993J	216	3.2

resolutions into the simulation and analysis procedures.

The relevant input parameters to the radiative neutrino decay simulation (not given in Table 1) are given in Table 2 for two sources, SN1987A and SN1993J. For both analyses the neutrino output ($\nu_\tau + \bar{\nu}_\tau$, say) of the supernova in neutrinos was assumed to be 6.3×10^{58} MeV with a Fermi-Dirac temperature of 8 MeV. Figure 1 shows the exclusion region in (m_ν, τ_ν) -parameter space from the SMM observations of SN1987A [6] (currently the best limits) assuming a branching ratio to a radiative decay mode of 1. Figures 2 and 3 show the exclusion regions obtained in the simulations for both SN1987A and SN1993J.

8. QUESTIONS

Question 1. We have developed software routines which perform the analysis procedures described above - Does the COMPTEL team have similar software which can be used to compare our results?

Question 2. Do the tables for the geometrical absorption factor (g), the effective area (A), and angular and position resolution exist for the range of energies and/or observational periods for which we are interested?

Question 3. We have used a dataspace of the size $80^\circ \times 80^\circ \times 60^\circ$ for (χ, ψ, ϕ) . Based on the experience of the COMPTEL team what are the suggested bin sizes in COMPTEL dataspace?

Question 4. How can we get access to the background models or estimates made for each of the viewing periods of interest?

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